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The seasonal variation of undercurrent and temperature in the equatorial Pacific jointly derived from buoy measurement and assimilation analysis

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Abstract

Based on the TOGA-TAO buoy chain observed data in the equatorial Pacific and the assimilation analysis results from SODA(simple ocean data assimilation analysis), the role of the meridional cells in the subsurface of the tropical Pacific was discussed. It was found that, the seasonal varying direction of EUC(the quatorial Undercurrent)in the Peacific is westwards beginning from the eastern equatorial Pacific in the boreal spring. The meridional cell south of the equator plays important role on this seasonal change of EUC.On the other hand, although the varying direction is westwards, the seasonal variation of temperature in the same region gets its minimum values in the boreal autumn beginning from the eastern equatorial Pacific.The meridional cell north of the equator is most responsible for the seasonal temperature variation in the eastern equatorial Pacific while the meridional cell south of the equator mainly controls the seasonal temperature change in the central Pacific. It is probably true that the asymmetry by the equator is an important factor influencing the seasonal cycle of EUC and temperature in the tropical Pacific.

Key words: the tropical Pacific, Equatorial Undercurrent, seasonal variations, meridional cell

1 Introduction

The happening time of ENSO event is frequently related with the phase lock of seasonal cycle. Predictability of ENSO can exhibit seasonal dependence(Cane et al., 1986; Webster, 1994). Nonlinear interaction of the annual cycle and the coupled ENSO mode leads to ENSO chaos in the intermediate and simple models (Jin, 1996; Tziperman et al., 1994). Theories of ENSO have made great progresses in the past decades beginning from the hypothesis by Bjerknes(1969). The essence of the Bjerknes's postulate is that ENSO arises as a self-sustained cycle in which anomalies of SST in the Pacific cause the trade winds strengthening or slackening, and the wind in turn drives the ocean circulation changing the anomalous SST. Numerous characteristics were studied in the zonal ocean-atmosphere interactions, e.g., the role of westerly burst in the western tropical Pacific, the unstable coupled waves, the delayed oscillator or the vanishing of the EUC on the equator during an El Nino (Philander et al., 1984; Schopf and Suarez, 1988; McPhaden et al., 1998). The fact of phase lock of ENSO with annual cycle im-

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plies that, the seasonal cycle itself is an important background in the formation of ENSO event.

The seasonal variation of SST has long been analyzed in the early period of ENSO studies. Figure1 gives its fundamental features that the direction of seasonal change in the tropical Pacific is westward. The warmest SSTs in the cold tongue occur in boreal spring, and the coolest SSTs occur in boreal autumn(Horel, 1982; Reynolds and Smith, 1995). The westward progression of the annual cycle of SST along the equator in the Pacific is related to the westward progression in the zonal winds (Xie, 1994; Chang, 1994). The zonal westward trade wind over a large area of the tropical Pacific leads to an asymmetric distribution of temperature along the equator: in the eastern tropical Pacific, the mean thermocline depth is much shallower than that in the western tropical Pacific. Previous studies (Delcroix and Henin, 1989; Kessler, 1990; Kessler and McCreary, 1993) have described the seasonal cycle of upper ocean thermal structure based on the dynamics of Ekman pumping and Rossby waves.

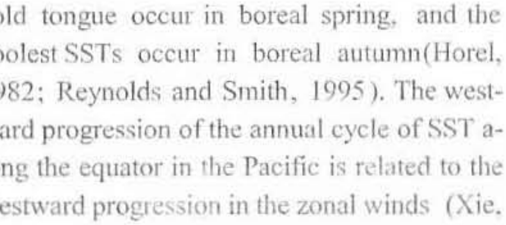

Fig. 1. The distribution of the tropical Pacific sea surface temperature and its seasonal change direction [after Horal(1982)]

The mean seasonal cycle of the EUC(the Equatorial Undercurrent)in the tropical Pacific has been described in many studies (Halphern, 1987; McPhaden and McCarty, 1992; McCarty and McPhaden, 1993; Weisberg and Hayes, 1995; McPhaden et al., 1998). The EUC is located in the upper thermocline. The maximum core of the EUC is found at greater depths in the west than in the east. The seasonal appearance time is seemingly in boreal spring at all latitudes (McPhaden et al., 1998).

The width of the EUC is about 200 km centered on the equator, at the depth of the order of 100~200 m. Water in the core has been detected to come from subtropical gyres(Fine et al., 1981; Fine et al., 1987; Tsuchiya et al, 1989). In a diagnostic model results(Bryden and Brady 1985), the linkage between the EUC and the high latitude was illuminated. The potential vorticity principium was first used to illuminate the dynamics of the EUC and a reasonable velocity order was estimated by Fofonoff and Montgomery (1995). Great progress was made in an inertial theory of the Equatorial Undercurrent (Pedlosky, 1987, 1996). Along the equator eastward, the gathering of streamline and the shallowing of the thermocline were shown to increase the speed of EUC in the inertial theory.

In the study of ENSO dynamics, the seasonal increase of SST in the equatorial Pacific in springtime is related with the reversal flowing of the South Equatorial Current(Halpern, 1987) resulted from annual relaxation of the trade winds(Chao and Philander, 1991; Yu et al., 1997).

The relation between the seasonal decrease of SST in the equatorial Pacific and the circulation has not yet well discussed. Neither is discussed the seasonal appearance of maximum velocity in the annual cycle of the EUC. Wang et al. (2001) gave the seasonal variations of the EUC at 130°E, Pu et al. (2001) had studied the volume transport by the equatorial currents, but their work discussed little on the mechanism of the seasonal variation of the EUC. In the second section of this paper, the data used in the analysis will be introduced. In the third section the characteristics of seasonal cycle of temperature and the EUC along the equator will be described and in the fourth section, the relations among the seasonal cycle of temperature, the EUC and the meridional cell in the upper layer will be dis-

cussed.

2 Data description

(1) Daily observational ADCP data from TOGA-TAO lasted from 1988 to 2001. The observational periods at 165°E, 170°, 140° and 110°W are all around 10 a from depth at 30 to 250 m bellow sea surface.

At longitude 147°E, the observational period between depths 50 and 250 m is round 6~9 a. Thus the averaged result in these depths can represent more information of the EUC.

(2) Monthly mean temperature and velocity provided by a simple ocean data assimilation (SODA) analysis(Carton et al., 2000).The grid interval in the product is 1° in zonal direction and variable in meridional direction. In order to compare the assimilated data with the observations by TOGA-TAO,data from 1988 to 2001 were studied.

3 The seasonal variations in the eastern equatorial Pacific

In the TOGA-TAO ADCP observations, only 4 buoys lasted around 10 a(see Fig.2). Seasonal variations of temperature and current in the equatorial Pacific would be discussed at these 4 sites, namely, at 110°, 140°, 170°W and 165°E.

3.1 The EUC

The seasonal variations of zonal current at 4 sites along the equator were shown in Fig. 3. It is obvious that, there are annual maximum velocities of the EUC at all these longitudes. At 110° and 140°W, the stage with maximum velocity is persisted during March and June, the velocity at 140°W is a little larger than that at 110°W. At 170°W, the persisting time with maximum velocity in the EUC appears much later than that located at 110° and 140°W. The latest site with maximum velocity in the EUC is 165°E, from June to August. Along the equator, the velocities of the EUC increased eastward from 165°E to 140°W, as the monthly results derived from currentmeter (McPhaden et al., 1998). According to the inertial theory of EUC, the slower of velocity at 110°W(see Figs 2a and b)than that 140°W (see Figs 2c and d)implies that the shadow zone(Pedlosky, 1996) in the Pacific may be between 140° and 110°W. East of 170°W, the minimum depths from the EUC core to the surface are also at the persisting period of maximum velocity. In the eastern equatorial Pacific, this persistent time corresponds to the annual trade wind relaxation stage.

3.2 The temperature

Figure.3 gives seasonal temperature variations at 4 sites along the equator. It is clear that the amplitudes of seasonal variations in the eastern tropical Pacific are larger than those in the western regions. The lowest SST appears in September at 110 °W, in November at 140°W and in February at 170° W.The same seasonal variations from the assimilated results in Fig.4 clearly show that, although averaged from 1988 to 2001, the main seasonal variations of temperature cycle from the data set of SODA are quite similar with those of from TOGA-TAO. As the assimilated data can present more dynamical massage, it will be convenient to use the data from SODA instead of other lonely observed data to discuss the possible mechanisms influencing the seasonal variations.

It can be observed from Figs 2 and 3 that, the annual cycles of temperature, maximum velocity and depths of EUC core to the surface didn't in phase with each other. What do these phase differences determine? If inertial equatorial undercurrent theory was being used in explanation (Pedlosky, 1996), the seasonal variation of meridional cell must be discussed first. The assimilated results from SODA are well represented the main seasonal cyclonic charac-

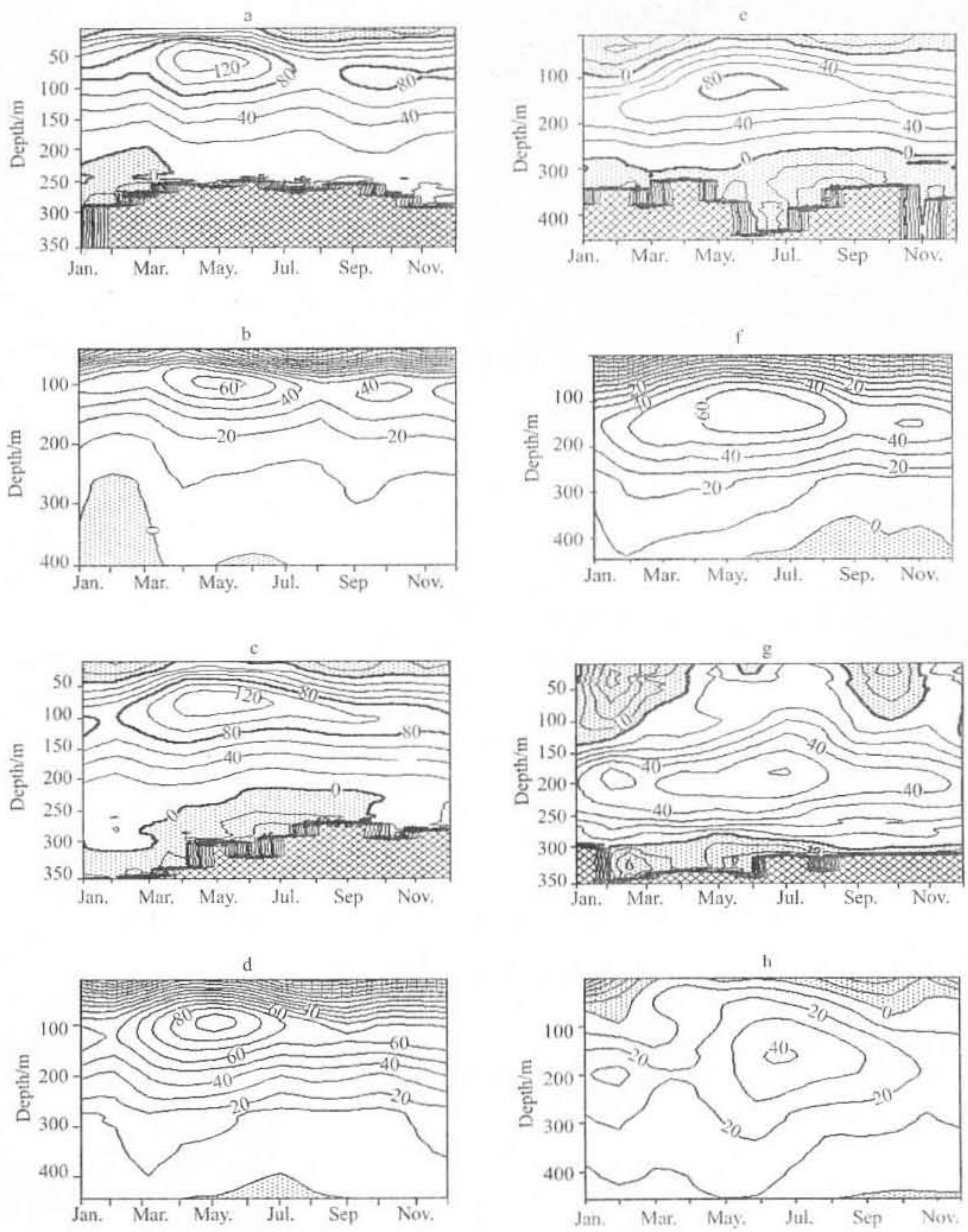

Fig. 2. Time-depth cross-sections of 14 a averaged current(cm/s) along the equator observed from ADCP of TOGA-TAO and assimilated by SODA at 110°W (a, b), at 140°W(c, d), at 170°W (e, f) and at 165°E (g, h). Values bellow 0 is dotted. Lacking of observations is shown as cross lined .

teristics as TOGA-TAO observations except the slowness of EUC at 165°E.The slower in the assimilated data than the observed velocity of the EUC may result from the lack of message along the equator.

3.3 The meridional mass transports

The width of EUC is approximately

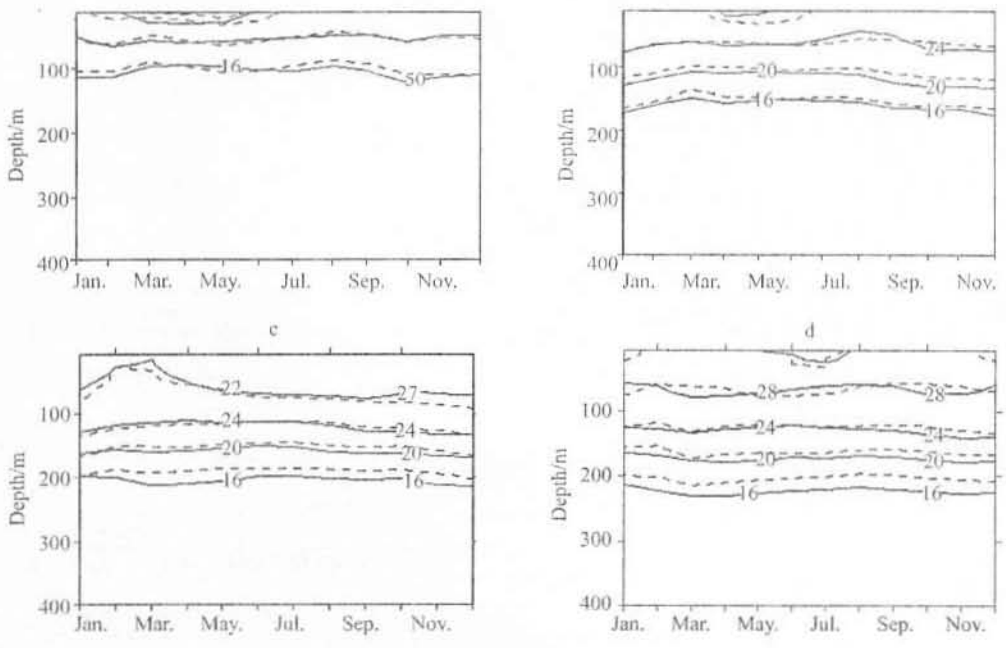

Fig. 3. Time-depth cross-sections of 14 a averaged temperature(°c) along the equator observed from TOGA-TAO (dashed lines) and assimilated by SODA (solid lines) at 110°W (a), at 140°W (b), at 170°W (c) and at 165°E (d).

200 km centered on the equator (Pedlosky, 1996). Locations around 1°N or 1°S will be best give the experience of how much water can be feed into the EUC.

The volume transport in the upper layer at edges of the EUC is shown in Fig.4. It can be seen that, corresponding to the relaxing of trade wind in boreal spring, pole-ward transport in both hemisphere reached minimum(see Figs 4c and d). During this time the equator-ward transport at north edge of the EUC was also get its lowest value of transport(see Fig.4a). It was only in Fig.4b that, the lowest equator-ward transport appeared in August. While in boreal spring the transport at the south edge of the EUC got its maximum value instead.

At the north edge of the EUC, most amount of water flow equator-ward was at the longitudes of 140°E and from 180°E to 115°W, while at the south edge,most amount of water flow equator-ward was at the longitudes from 175°E to 140°W.

4 The influence of the meridional currents upon the seasonal cycle of the temperature and the EUC

Figure 5 gives the seasonal cycles at 4 sites along the edge of the EUC in both hemispheres. It is obvious that, at 110°W north of the equator, there is a strongest meridional current during August and September corresponding to the minimum SST during the same period (see Figs 4a, c and d, and Fig. 5a). At 170°W south of the equator, there is a strongest meridional current appeared in February corresponding to the minimum SST during the same period (see Fig. 5e). At 140°W north of the equator, there also exists a strongest meridional transport corresponding to the minimum temperature in November (see Fig. 5c).

The pole-ward Ekman transports are responsible for the SSTs in the tropical oceans

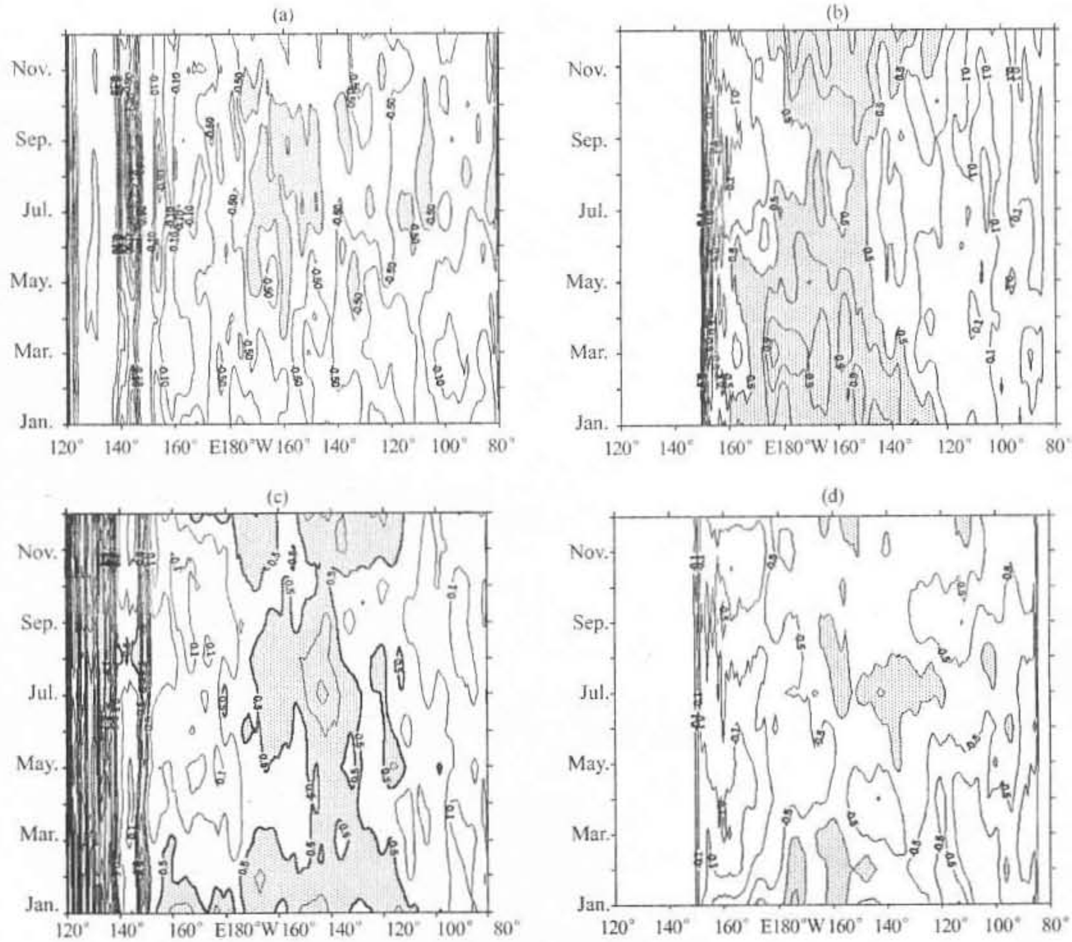

Fig. 4. Longitude - time section of equator- ward (a,b) northwardc(c) and southward(d) monthly mean transportation in the upper 300 m layer at 1.352 3°N (c,a) and at 1.352°S(b,d) (values less than −0.5 are dotted (b,c).)

(Wyrtki and Koblinsky, 1984). The upwelling in the equatorial ocean decreased the temperature in the upper layer, especially in the eastern tropical ocean.But the equator-ward meridional transports contributed to the seasonal cycle differently. It can be realize that the Ekman effect represented by the meridional cell in the upper ocean can be the important influence on the decrease of SST in the region of the equator.At 110°W is in September, at 170°W in February and at 140°W in November. Thus it can be concluded that, the meridional cell driven by the Ekman transport is the main affection in determining the minimum SST in annual cycle.

It can be noted from Figs 2 and 3 that, the vertical temperature gradients are strengthened when the EUC reached its annual maximum. More stratification in the surface layer of ocean prevented the EUC from losing of momentum in the subsurface layer,which can favor the increase of velocity in the EUC.

Calculations and comparisons were made in the zonal velocity gradient along equator and meridional velocity gradient in the polar-ward direction (figures were omitted). It was found that, values of zonal velocity gradient are one order less than values of meridional velocity gradients. Thus the meridional convergence may be regarded as the main factor affected the strength of EUC.

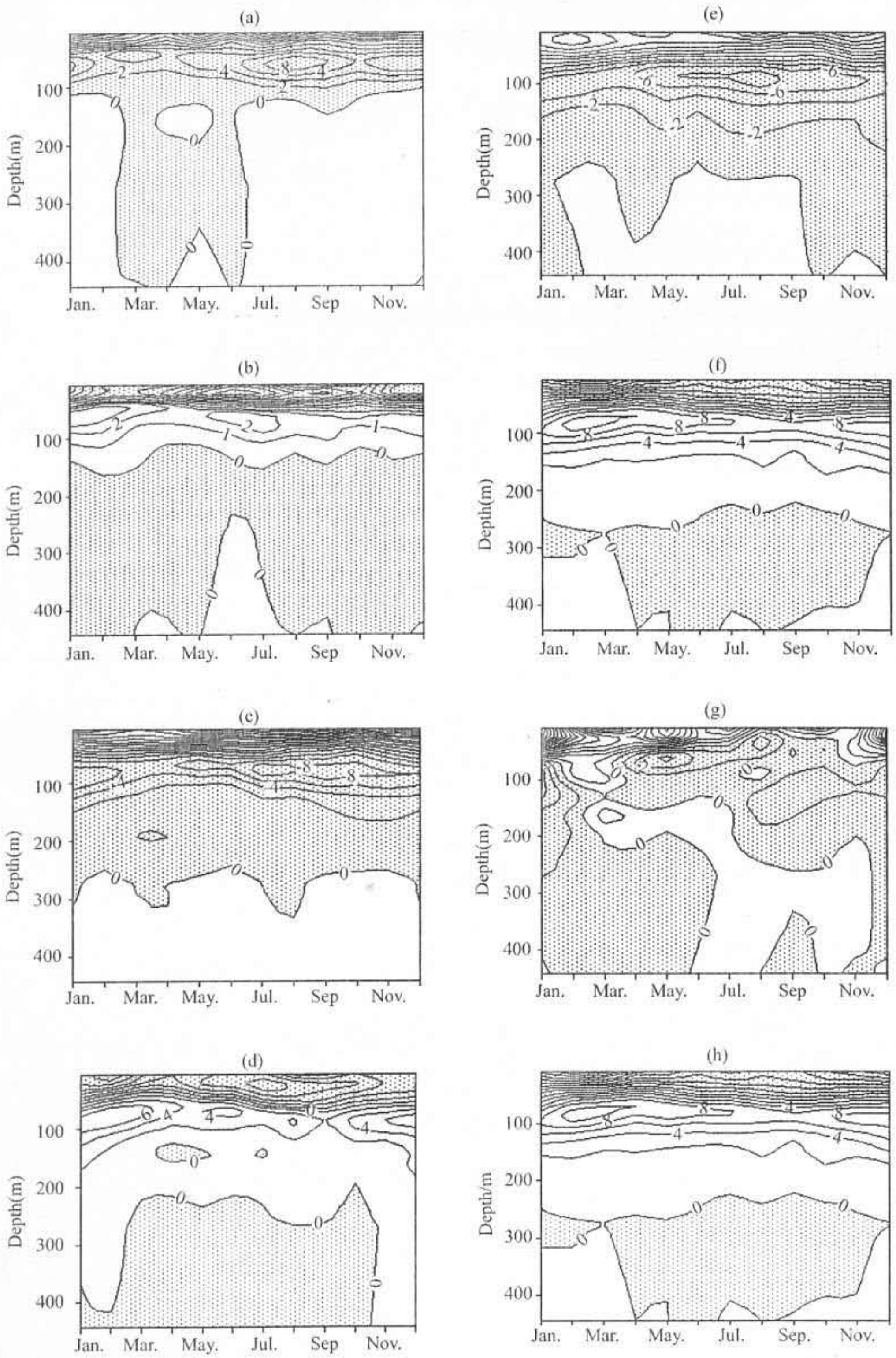

Fig. 5 . Time-depth sections of meridional component of velocity(cm/s) along 1.352 3°N (left panels) and along 1.352 3°S (right panels)(Negative values are dotted). At 110°W(a,b), at 140°W (c,d), at 170°W (e,f) and at 165°E(g,h).

As for the maximum in the annual cycle of EUC, transport in the subsurface layer to the equator seems to affect a great extent at 170°W (see Fig. 4b). This conclusion can be true at this longitude because as discussed in Section 3, the intensified equator-ward flow appears in its nearby, especially from the Southern Hemisphere. East of this location, at 140° and 110°W, the zonal current will be affected by the meridional transport from the distances parallel along the equator. At 110°W, a strengthening of meridional flow from the south of equator in February may cause the increasing of the EUC. If we look into the longitude west of 140°W in Fig. 4 in March, the relation between the intensity of zonal current and the meridional convergence may be easily explained.

5 Discussion and conclusions

The analysis in the previous sections showed that the seasonal cycle of the temperature and the EUC in the equatorial Pacific have different affections. The cycle of temperature is affected by the intensity of meridional cell in upper layer.By influencing the upper divergence, the wind-driven Ekman transportation can affect the SST directly.The meridional equator-ward flow in the subsurface Southern Hemisphere is not in phase with the divergence in the upper layer, this implies remote forcing in the south Pacific may take affection in seasonal cycle temperature and the strength of EUC. A simplified mechanism can be presented to explain the seasonal minimum value of SST and maximum value of EUC in the following schematic diagrams.

Since the intensification of meridional cell have different special and temporal at north or south of the equator, thus from the characteristics revealed in Fig.6. It can be concluded that, at 140°W, the decrease of SST in the seasonal cycle is mainly influenced by the meridional cell north of the equator while the intensification of the EUC is controlled by the meridional flow from south of the equator. This implies that the south Pacific may take important roles in the climate change because the transportation of water may take affections on the water temperature in the equatorial eastern Pacific in longtime range (Gu and Philander, 1997). At the central Pacific of 170°W, the situation is quite contrary with that at 140°W. From Fig.7, the decrease of temperature in the seasonal cycle is mostly affected by the meridional flow south of the equator while the increase of the EUC there is much affected by the meridional flow north of the equator.

The study in this work supports the undercurrent theory presented by Pedlosky (1996) in two characteristics; the increase of velocity along the equator and the maximum velocity appear at the stage with shallow depth from the core to the sea surface.

It can be induced that, as discussion for the atmosphere-ocean coupled system (Jin et al., 1994), the meridional cell may have some affection on the irregularity of El Nino. Now that the meridional cell controls the seasonal cycle of temperature and EUC in the tropical Pacific, why can't it be affect the happening of El Nino? If this thought is proved to be true, then the tropical atmosphere-ocean coupled system will be no longer an isolated system as the system described by Cane et al. (1986). The characteristics of affections that the meridional transports

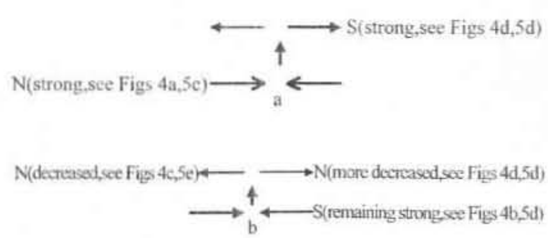

Fig. 6. Schematic diagram for causing seasonal minimum SST (a) and maximum EUC (b) at 140°W.

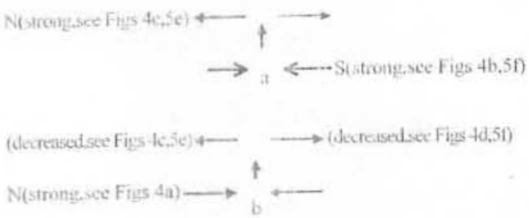

Fig. 7. Schematic diagram for causing seasonal minimum SST (a) and maximum (b) at 170°W.

affect the tropical ocean during the El Nino and La Nina events will be discussed in our further work.

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